

# Precision Automatic Co-Registration Procedures for NASA Sensors

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**Abstract-** Precise change detection and analysis of low (e.g. 1-4km weather satellite) and moderate (e.g. 30m Landsat) resolution space sensors involves the application of techniques that assure sub-pixel co-registration and orthorectification of satellite imagery. The procedure is "automatic" in the sense that human-initiated tiepoint selection is not required, but rather the ephemeris information associated with an image is relied upon to initiate the co-registration process. The methodology employs the additive composition of all pertinent dependent and independent parameters contributing to image-to-image tiepoint misregistration within a satellite scene. Mapping and orthorectification (correction for elevation effects) of satellite imagery defies exact projective solutions because the data are not obtained from a single point (like a camera) but as a continuous process from the orbital path. Standard image processing techniques can apply approximate solutions with sufficient accuracy, but some advances in the state-of-the-art had to be made for precision change-detection and time-series applications where relief offsets become a controlling factor. The basic technique first involves correlation and warping of raw satellite data points to an orthorectified Landsat data base to give an approximate mapping. Then digital elevation models are used to correct perspective shifts due to height and view-angle of the imaging platform. To avoid degradation of the data by multiple resampling, each warp is represented by an ultra-fine grid of tiepoints. For successive warps, the grids can be composed mathematically into a single grid such that only one re-sampling occurs after all relevant calculations are complete. Ultra-fine grids can currently be up to 1000 x 1000, or one million points.

## Introduction

The remote sensing community has been more concerned with co-registration of images than the comprehensive image rectification concerns of the photogrammetry community [1,2,3,4]. Terrain effects have been considered of minor impact by the remote sensing community until recently, when (a) higher resolution systems became available, (b) a greater emphasis on satellite data integration with GIS for business applications occurred, and (c) change detection and data fusion studies became more prevalent. For example, studies on the impact of mis-registration on change detection analysis showed that misregistration of only one pixel can cause up to 50 percent error in some change detection applications [5] and in most applications change detection is confused by misregistration [6,7]. The emerging standard for remotely sensed imagery data transfer has identified the basic requirement for orthorectification processing as well as adherence to map projection and datum accuracy standards and annotation [8,9]. It is the adverse impact of the independent variable of terrain upon pixel position knowledge that continues to demand attention despite our good understanding of

satellite ephemerides (position and attitude) and sensor geometric properties. Many sensor systems (e.g. AVHRR, MODIS, GOES, and Landsat) employ line scan designs that view off-nadir as much as 55 degrees, while other sensor systems with pushbroom imaging designs (e.g. ASTER and Hyperion) regularly acquire off-nadir views of as much as 25 degrees.

The development of our automatic orthorectification and mosaicking system of procedures has relied on two key recent developments. The first is the general availability of DEMs with 1 arc second posting (nominally 30 m) for much of the US and the upcoming release of DEMs for the world's landmass between 57 degrees N/S from the Shuttle Radar Topography Mission (SRTM) [10]. This permits the preparation of orthorectified satellite imagery using similar techniques to those developed by the photogrammetry community for aerial photographs. The second is the preparation of a complete set of orthorectified Landsat TM images for the world's landmass by the Earth Satellite Corp. for the NASA/Stennis Commercial Data Buy Program [11]. These two developments provide the key datasets necessary to prepare a baseline image dataset to which all satellite imagery datasets having a pixel resolution of 10m or greater can be automatically orthorectified to sub-pixel accuracy.

## Methods

The image processing system we use, Video Image Communication And Retrieval (VICAR) started development in 1962 and has accumulated hundreds of processing routines over the years [12]. A major feature of VICAR, and also of other major image processing systems is the ability to string together a command-line sequence of standard processes (each coded as a computer program) to accomplish a complex task. We were attracted to the possibility of applying a sequence of these programs to the problem of map projecting and co-registering space-based sensor data.

The contemplated steps were:

1. Sensor-specific corrections (e.g. edge of scan overlap ("bowtie") correction of MODIS and AVHRR datasets).
2. Map projection using three image corner points (obtained from the satellite file information). Presently always from a rotated UTM projection to Platte Carre' projection.
3. Application of the provided satellite image Latitude/Longitude reference grid as a residual to the mapping. Note: this is provided with ASTER, MODIS, AVHRR and GOES images, but not for Hyperion or Landsat images.

4. Corrective mapping using ortho-rectified Landsat [11] mapped data as a base uses a 2-D FFT correlation [13] of the sensor data to the ortho-rectified Landsat to generate tiepoints for a input to a quadratic model for image warp. The quadratic model approximates tiepoint off-set errors associated with along- and across-track position knowledge, and roll/pitch/yaw elements not explicitly accommodated for by the ground data processing system.
5. Elevation correction (using digital elevation models and view angle of space platform to pixel).
6. Co-registration of a second acquisition to a first acquisition (using 2-D FFT correlation tiepoints of the second image to the first).

However, there were two major flaws in this plan. First, was the need to continuously keep track of each pixel's geolocation, which required the addition of file parameters that tracked pixel scale size and raster geography (map datum and projection). This was accomplished through the use of GeoTIFF file extensions added at each step in the image processing chain[14]. Second was the recognition that each operation that moves pixels in an image processing system, known as a warp, resamples the input pixels to calculate the output pixels causing a degradation of the data. This degradation occurs whether one uses a nearest-neighbor resampling, which incurs spatial degradation, or a bilinear or spline resampling, which incurs radiometric degradation. When images are mapped or registered, resampling has to be performed, but we asked ourselves if there was any way that the resampling could be kept to this minimum of one within an image processing system context.

The alternative of combining all of the steps of an image processing system into a single computer program was considered. This design would go way beyond turning the image processing programs into subroutines, because the sequence of steps would have to be applied to each pixel value, requiring the central execution loops of each program to be strung together in a single execution loop. Reprogramming in this way would be extremely programmer intensive and have a high chance of programming failure.

#### ***Ultra-Fine Grid Methodology for Image Processing***

The solution devised for this problem was to create an additional datatype standard in the VICAR system. The data type, called an *Ultra-Fine Grid*, is a grid that pairs up with an image to specify how it is warped to produce an output image. The VICAR system has always used grids to specify warps, and had programs that perform the warp of the image using the grid. However, the grid was limited to about a 30 x 30 grid, typical of all image processing systems. This size of grid does not allow for a very accurate warp unless the warp is fairly smooth [15,16]. Using differential geometry, one can show that the error between grid points is approximated by the difference between a secant and an arc of a circle. The maximum of this difference decreases four times as the secant is halved. Thus, a grid of 1000 x 1000 will decrease this secant error by a factor of over 1000 compared to a 30 x 30 grid. The grids are composed of floating or double precision numbers. That is, they can reference between the pixels that they refer to.

The second step of this solution is to have all relevant programs produce or use ultra-fine grids. The relevant programs are:

1. the warping program
2. the elevation correction program
3. the 2-D FFT image correlation program.

In addition, there is a key program that can convert non-grids into ultra-fine grid format. For example, the output from correlation is rarely a grid, since bland areas may not correlate. This program needs at least two modalities for converting non-grids to grids: (a) polynomial fits and (b) piece-wise linear fits.

The final key to this solution is a program that can compose two initial ultra-fine grids into a single ultra-fine grid. Repeated application of this program would then be able to compose all of the image processing steps, each of which has its own grid, into a single grid (see Figure-1). The Composed Gridding approach avoids the problem of coarse gridding found in the classical image processing techniques of piecewise transformation or polynomial-based geometric correction algorithms, known to introduce horizontal position errors in even the flattest terrain [15,16]. Nor does it use the approach of reducing Digital elevation models to triangular irregular networks (TINs) common in digital photogrammetry to lower ray-tracing computation [17,18]. Rather, it employs a new algorithm for image-to-image tiepoint generation that can efficiently accept up to one million points, or a 1000x1000 matrix. The procedure allows multiple steps to be performed by a toolbox of routines, each outputting an ultra-fine grid. The grids from the steps are mathematically combined into a composed ultra-fine grid. While every sensor is a unique case, the toolkit of routines can address each type of systematic and erratic component associated with horizontal adjustments. Since the grids are floating point numbers, they do not contribute to a resampling type error as the composition process takes place. Care must be taken so that the earlier transformations do not introduce errors that cannot be removed by later transformations. As an example of this, the 11 x 11 mapping grid provided with the ASTER satellite data, which must be applied after the data are mapped into Platte Carree' (longitude-latitude) coordinates, otherwise the secant error of the 11 x 11 cells would be large and non-correctable.

#### ***Processing Steps Using Ultra-Fine Grids***

The processing becomes a cycle or iteration through the steps that are necessary to produce the final image (see Figure-1). For example, image correlation might be the third step. The first two steps are performed, the first two resulting ultra-fine grids are composed and the resulting grid is used to warp the input into a partially corrected output. This output then becomes an input into correlation. The output from correlation is turned into a new ultra-fine grid which can then be used with the previous two to produce a third stage partially corrected output. The last cycle of this cyclic process produces the final output. Some stages might not need the actual image, for example, the elevation correction works on the grid only. At the present time, the bowtie correction applied to whisk-broom sensors (MODIS and AVHRR) is carried out as a separate resample. This resample only affects pixels in the bowtie overlap area.

Calculating absolute as well as relative position error bounds for each of the steps is quite difficult. Calculating

a position and error bound for the overall process is even more problematic since some of the later steps correct errors from earlier steps. At the present time we are looking at the visible errors in the final products, relative to either two co-registered images to a source map and the Landsat ortho-rectified base image, as a measurement of the accuracy of the overall process.

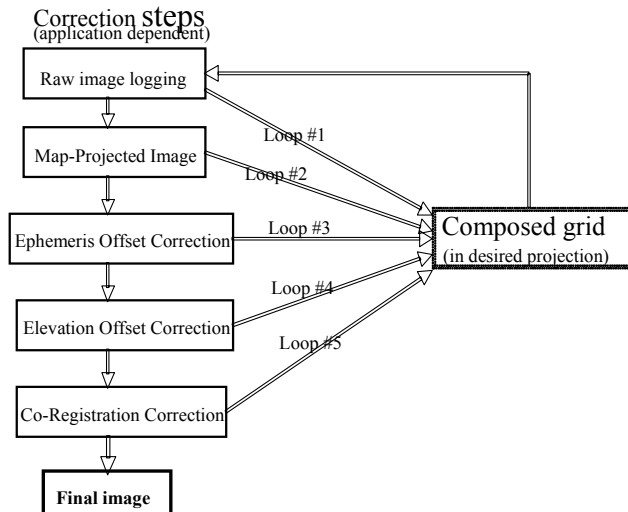


Figure 1. Composed Gridding Concept

The VICAR image processing system allows for the steps of a complex process to be set up as a user-friendly procedure with input parameters that name the raw data sets. We have set up procedures for several space-based sensors as described in the next section.

### Case Studies Review

Five case studies are described to illustrate key functions developed, and how they are combined for an application to automatic co-registration.

The first case study, AVHRR time series co-registration, exercised all of the functions associated with orthorectification of satellite images to a common reference base, and, by definition to each other, thereby permitting accurate change detection and time series analysis. The NOAA/POES/AVHRR has important systematic geometric distortions associated with expanding latitudinal coverage as the spacecraft progresses poleward and progressive distortions associated with the whisk-broom scanner that points up to 55 degrees off-nadir. The POES/AVHRR also experiences erratic geometric distortions associated with incomplete position and attitude knowledge. As the orbit of the POES/AVHRR is allowed to perturb daily, orthorectification for co-registration must be performed under varying conditions for each scene.

The second case study, MODIS *Terra* and *Aqua* scene co-registration, was able to utilize the per pixel geometry information provided in an ancillary file with the MODIS instrument data. Latitude, longitude, and scanner incidence angle to the earth geoid are provided, reducing the co-registration problem to systematic incorporation of

elevation offsets, which are only a few pixels at the most for the 1km resolution bands.

The third case study, Landsat-7 co-registration, required a more rigorous co-registration using a 1 arc second (~30m) digital elevation model to accommodate the horizontal offset at the scene edges caused by up to 7.5° look-angles off-nadir of the whisk-broom sensor and account for the higher pixel resolution (30m).

The fourth and fifth case studies, ASTER and Hyperion imagery co-registration, required the similar use of a 1 arc second (~30m) digital elevation model to accommodate horizontal offsets of their high-resolution pixel datasets (15m and 30m). These Push-broom line array sensors are better behaved than whisk-brooms, but the instruments can view as much as two orbit paths on either side of their current nadir path, with the result that earth-incidence angles of over 20° needed to be accommodated.

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